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# REGULATION OF THE DEGREE OF DISPERSION OF LIQUID AEROSOLS OBTAINED BY THE CONDENSATION METHOD

A. G. Amelin and M. I. Belyakov

Liquid aerosols are obtained by two methods differing in principle: mechanical pulverization of the liquid and the condensation method. The great advantage of the condensation method for the production of liquid aerosols lies in its cheapness and simplicity. The explanation is that in the condensation method the subdivision of the liquid takes place by using the energy of combustion of the fuel and is effected without the use of cumbersome and complex compressors which are generally used in mechanical subdivision of liquids.

The simplest method for the production of liquid aerosols by the condensation method consists of mixing the vapors of the toxic agent, or of a mixture of vapors of the toxic agent and a solvent, with air, in this case the liquid aerosol is formed as the result of the condensation of the vapors in the space on mixing with the colder air.

The required droplet size in the aerosol cloud varies in accordance with the nature of the object to be treated [1]. For example, in the treatment of closed premises it is desirable to use an aerosol cloud consisting of droplets of the smallest possible size. Conversely, in the treatment of field crops the presence of small droplets in the aerosol cloud is undesirable, as such droplets are carried long distances by the wind and are not utilized in practice. Therefore, aerosol equipment should ensure the regulation of the degree of dispersion of the aerosols produced within wide limits. However, experience shows that in the condensation method liquid aerosols are usually obtained with a very high degree of dispersion and for this reason their field of application is limited.

Condensation of vapors in space and formation of liquid droplets takes place in presence of supersaturated vapor, when the supersaturation reaches the critical value or exceeds the critical value. This may be expressed by the equation

$$S = S_{cr} \quad (1)$$

and

$$S = \frac{p}{P_s} \quad (2)$$

where  $p$  and  $P_s$  are the vapor pressure in the gas and the saturated vapor pressure. As the saturated vapor pressure  $P_s$  is a function of the temperature, equation (2) may be written:

$$S = \frac{p}{f(T)} \quad (3)$$

It follows from equation (3) that, in order to determine the supersaturation of the vapor which occurs and so to establish the possibility of space condensation of the vapor, it is necessary to know the pressure of the vapors in the gaseous mixture and the temperature of this mixture. These values depend on the quantitative ratio of the mixing streams, which may be expressed by the following equations:

$$P = f(n), \quad (4)$$

$$t = \varphi(n), \quad (5)$$

$$n = \frac{q_1}{q_2}, \quad (6)$$

where  $q_1$  and  $q_2$  are the amounts of the first and second gas. It follows from equations (4-6) that supersaturation of the vapors is also a function of the quantitative ratio of the mixing streams, i.e., it depends on the coefficient  $n$ .

The mixing of the vapors of the liquid with air in the production of liquid aerosols is usually effected in a stream, and therefore, in the present work a study was made of the regulation of the degree of dispersion of liquid aerosols obtained in a free stream.

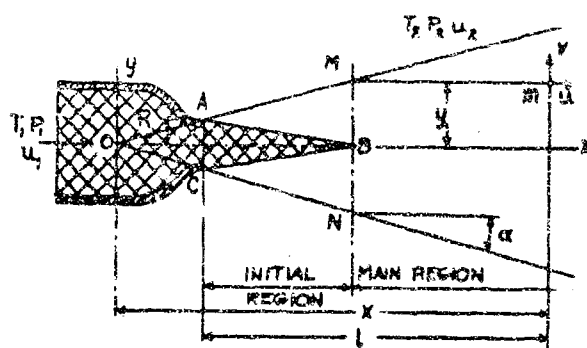


Fig. 1. Diagram of free stream (explanation in text).

The free stream is diagrammatically represented in Fig. 1. The vapor-gas mixture at a temperature  $T_1$  and vapor pressure  $P_1$  emerges with a velocity  $u_1$  under a certain excess pressure from the jet 1, which consists of a tube with an opening of radius  $R$  at the outlet. As the result of contact with the air, the velocity of which is  $u_2$ , the temperature  $T_2$ , and vapor pressure  $P_2$ , some air is sucked into the region of the stream and mixes with the gas stream emerging from the jet. The region of mixing of the gases is limited by two straight lines, forming an angle of  $\sim 14^\circ$  with the axis of the stream; these straight lines meet at the pole  $O$  of the stream and determine the boundaries of the stream [2].

The region of the stream which starts at the edge of the jet  $AC$  and continues up to the section  $MN$  (the initial region of the stream) contains a central core of constant flow rates ( $ABC$ ). In this core, the values for the characteristics of the original gas stream, i.e., the gas emerging from the jet,  $T_1$ ,  $P_1$ ,  $u_1$ , remain unchanged.

If, for a certain point  $m$  within the stream, we denote the velocity component in the direction of the axis of the stream by  $u$ , and in the direction of the cross-section of the stream by  $v$  (Fig. 1), and if we assume that the origin of coordinates is at the pole of the stream, then the velocity of the stream along the  $X$  axis will be always positive, and along the  $Y$  axis it will be positive near the axis of the stream and negative near the boundary of the stream. This explains the entry of the surrounding gaseous mixture into the stream and the mixing of the gaseous streams.

It follows from the theory of free flow that in the main part of the stream the flow rate, temperature, vapor pressure, and vapor supersaturation at any point in the stream is determined by the position of this region, i.e., by the coordinates  $X$  and  $Y$ . Therefore, the values of these may be expressed by the equations:

$$u = u_1(X, Y), \quad (7)$$

$$t = t_1\phi(X, Y), \quad (8)$$

$$P = P_1\psi(X, Y), \quad (9)$$

$$S = \phi(X, Y), \quad (10)$$

where  $u_1$  and  $u$  are the flow rates;  $t_1$  and  $t$  are the stream temperatures, and  $P_1$  and  $P$  are the vapor pressures in the jet and in the stream.

In the production of liquid aerosols for combating agricultural pests, substances of high boiling point are generally used as solvents for the toxic agents. Therefore, when these vapors are mixed with air, which has a relatively low temperature, very high vapor supersaturation occurs in the field of flow.

Fig. 2 shows the values of  $t$ ,  $P$ ,  $u$ , and  $S$  along the axis of the stream, calculated for the mixing of air containing glycerin vapor with atmospheric air in a free stream. It is seen from these data that the changes of  $t$ ,  $P$  and  $u$  along the axis of the stream are similar in character; their values decrease with increasing distance from the transitional section of the stream. The vapor supersaturation increases at first, reaches a maximum value, and then decreases.

Fig. 3 shows the values of  $t$ ,  $P$ ,  $u$ ,  $v$ , and  $S$  at the cross-sections I, II, and III (Fig. 2). It is seen from Fig. 3 that the changes in  $t$ ,  $P$ ,  $u$  and  $v$  along the axis of the stream, i.e., along the  $Y$  axis, are also similar in character. In all the sections of the stream there is a uniform decrease in these values from the axis of the stream to its boundaries. In all sections of the stream vapor supersaturation passed through a maximum, and in some sections two maxima are found. The data for vapor supersaturation shown in Figs. 2 and 3 are arbitrary, as they were obtained without allowance for the condensation of the vapor in the space. The changes in the velocity of the gas flow along

the Y axis in different sections of the stream have the same character. The velocity of the gas flow commences at zero at the axis of the stream, then decreases, and assumes a negative value at the boundaries of the stream. The negative value of the velocity along the Y axis at the boundaries of the stream explains the entry of atmospheric air into the stream, which ensures mixing of the flows.

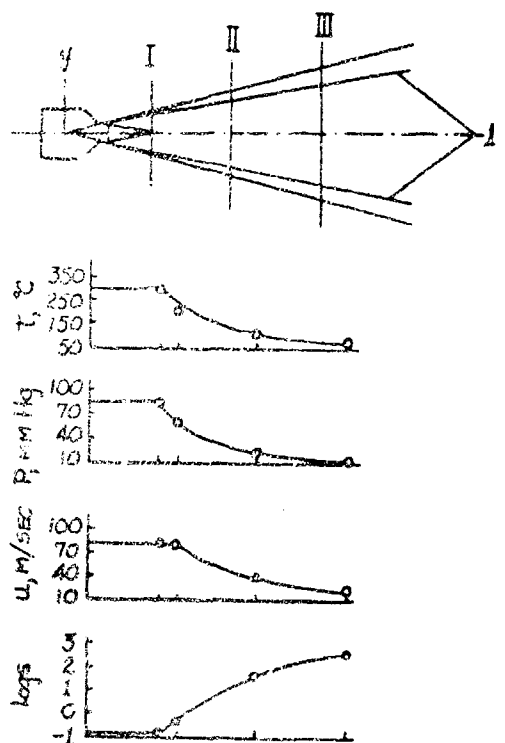


Fig. 2. Values of the temperature (T), vapor pressure (P) and vapor supersaturation (log S) along the axis of the stream; 1) the maximum supersaturation of the stream.

and may be calculated for each concrete case, it depends on the nature of the liquid and also on the nature of the mixing streams, and does not depend on the method of mixing [4].

In the production of liquid aerosols in a stream, the maximum supersaturation always exceeds the critical value, and it is always set up right by the edge of the jet. This is seen from Fig. 2, where the curve for the maximum supersaturation of vapor originates at the jet and passes through all the regions of the stream. Hence the condensation of vapors in the space and the formation of primary droplets commences right by the edge of the jet. Subsequent vapor condensation takes place on the surfaces of these primary droplets in the region where the supersaturated vapor is formed.

However, the process is retarded because in vapor condensation heat is evolved, which raises the temperature of the droplets, and this lowers the pressure difference which determines the vapor condensation rate at the droplet surfaces. Therefore, despite the existence of vapor condensation on the surfaces of the available droplets, the vapor supersaturation remains high, and as a result vapor condensation in the space and formation of new primary droplets occur simultaneously. Because of the high rates of flow in the stream, turbulent coagulation is of great significance, and as a result the droplet size increases.

Thus, in the field of the stream, formation of primary droplets and growth of previously formed droplets due to condensation of vapor on them and to coagulation, take place simultaneously. Therefore, the final droplet size, or the degree of dispersion of the aerosol formed, depends on the ratio of the velocity of formation of the primary droplets and the rate of vapor condensation on the surface of the existing droplets.

Hence, it follows that to increase the mean diameter of the droplets in the aerosol formed it is necessary to set up conditions in the stream which ensure the condensation of the major portion of the vapor on the surfaces of a small

The rate of droplet formation  $I$  and the droplet radius  $r$ , depend [3] on the vapor supersaturation and the temperature:

$$I = \varphi(S, t), \quad (11)$$

$$r = f(S, t), \quad (12)$$

Thus, with the aid of equations (7-12) it is possible to determine the number and dimensions of the droplets formed in the stream.

The condensation of vapors in the space and droplet formation take place as the result of condensation of the vapors at condensation centers which exist in the gaseous mixture or are spontaneously formed in it. In practical conditions the particles suspended in the air, and ions, have no significant influence on the process of formation of liquid aerosols, as the number of dust particles in 1 cm<sup>3</sup> of atmospheric air rarely exceeds 10<sup>4</sup>, while the number of droplets in 1 cm<sup>3</sup> of the gaseous mixture in the zone of their formation is 10<sup>9</sup>–10<sup>10</sup>; consequently, the formation of droplets of the liquid occurs mainly as the result of condensation of the vapors at condensation centers, which are of the nature of fluctuational coagulations.

When vapors are mixed with a colder inert gas, the supersaturation which arises is unequal in the region of mixing (Figs. 2 and 3); in some regions the highest or maximum supersaturation is set up. In reality this supersaturation is not always attained, as condensation of the vapors in the space and a decrease of supersaturation takes place before that. Maximum supersaturation of vapor is an important index of the process of new phase formation,

number of droplets, and therefore the probability of new droplet formation must be decreased as much as possible. Conversely, for a decrease of the mean size of the droplets it is necessary to set up conditions which ensure the formation of new primary droplets during the entire process of stream mixing, and to restrict the condensation of vapors on the droplets previously formed as much as possible.

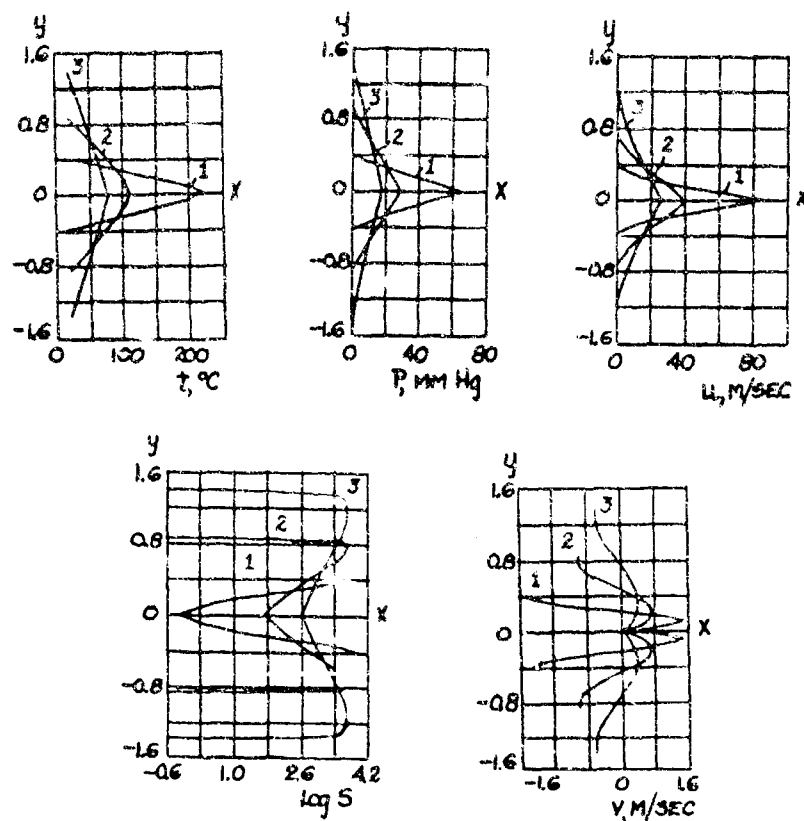


Fig. 3. Values of  $t$ ,  $P$ ,  $u$ ,  $\log S$  and  $v$  in various sections of the stream; 1, 2, 3 ) I, II, III sections (see Fig. 2).

The vapor pressure, temperature, and maximum vapor supersaturation in the field of the stream are practically independent of the velocity of the vapor-gas mixture in the jet: they are determined by the position of the point under consideration, i.e., by the coordinates  $X$  and  $Y$ . However, the flow rate in the field of the stream directly depends on the velocity of the vapor-gas mixture in the jet, and therefore, the lower is the velocity of the vapor-gas mixture in the jet, the lower is the velocity in the field of the stream, and this correspondingly increases the time during which the vapor-gas mixture remains in the region of supersaturated vapor. Hence it follows that the vapor supersaturation will be decreased by vapor condensation on the surfaces of the droplets formed at the start of the stream (near the jet) to an increasing extent with decreasing velocities of the vapor-gas mixture in the jet. The probability of formation of new primary droplets will correspondingly decrease.

From the above it follows that regulation of the degree of dispersion of liquid aerosols obtained by mixing vapors with atmospheric air in a stream, may be effected by variation of the velocity of the vapor-gas mixture in the jet. This permits relatively simple regulation of the degree of dispersion of aerosols in wide limits.

The time during which the droplets remain in the supersaturated vapor region is determined not only by the velocity of the vapor-gas mixture in the jet, but by the dimensions of the jet. This follows from the fact that the linear dimensions of the region in which supersaturated vapor is formed are determined by the coordinates  $X$  and  $Y$  and are in direct dependence on the jet diameter. Therefore, for a given velocity of the vapor-gas mixture in the jet, the time during which the droplets remain in the supersaturated vapor region depends on the jet diameter.

The aim of the laboratory investigations included the verification of these basic views. Fig. 4 shows a diagram of the laboratory apparatus.

The thermostat 1 contains, at a certain height from the floor, a coil evaporator 2, made out of glass tubing 25 mm diameter and having a total surface of 1107 cm<sup>2</sup>. To maintain the required temperature in the thermostat, it

contains a contact thermometer 2, suitably connected to the electrical heating system 4, which ensures regulation of the temperature to an accuracy of  $\pm 1^\circ\text{A}$ . A fan, 5, is installed in the thermostat to level the temperature. Air from the blower 6, after passing the flow meter 7, enters the evaporator, where it becomes saturated with glycerin vapor, and is then directed along the heated and insulated tube 8 to the jet, the dimensions and construction of which are varied according to the aims of the experiment. The temperature of the gaseous mixture at the exit from the evaporator and at the jet is measured by means of the thermocouples 10.

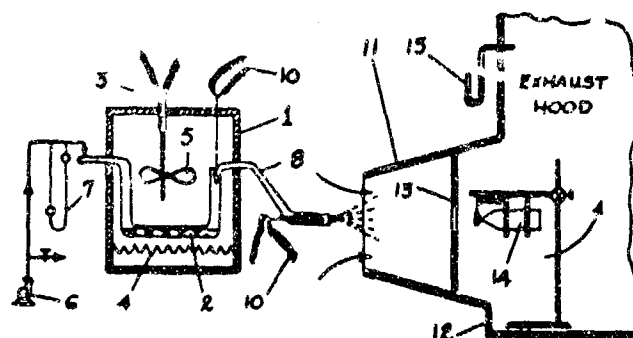


Fig. 4. Diagram of the laboratory apparatus for the preparation of liquid aerosols by the condensation method (explanations in the text).

The liquid used was glycerin, which has a high boiling point, and for which the necessary data for the subsequent calculations (surface tension, viscosity, vapor pressure, etc.) are available in the literature. It was also taken into account that glycerin was already used previously for studying liquid aerosols in laboratory conditions [6].

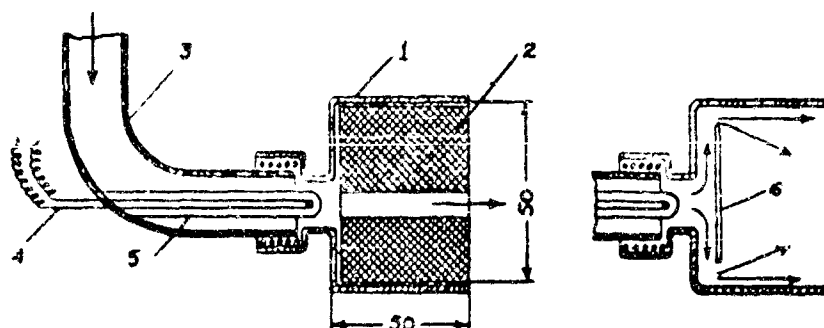


Fig. 5. Jet with metal tip (explanations in the text).

At the exit from the jet the glycerin vapor mixes with the colder surrounding air, vapor condensation takes place in the space, and an aerosol cloud is formed, which is drawn into the conical pipe 11, attached to the wall of the exhaust hood, 12. The conical pipe has a partition with a round opening in the middle, by means of which the aerosol cloud, diluted with air, goes toward the trap 14 for sampling. Equal sampling conditions are ensured by the fact that a constant reduced pressure, measured by the manometer 16, is maintained in the exhaust hood.

The degree of dispersion in the aerosol cloud is determined by counting the number of droplets in a certain volume of the cloud, and measurement of the diameter of these droplets. This method is very laborious, but it ensures reliable results.

For taking a sample of the aerosol cloud, a metal trap is used, in which two microscope slides are fixed. After a sample of the gas is taken, the trap is allowed to remain for 1 hour to allow the droplets to settle on the slides, and the slides are then examined under the microscope.

The jet used in the laboratory experiments was the iron funnel chamber 1 with a diameter of 50 mm and length 50 mm (Fig. 5). The insert 2 with openings of 2.5, 7.5, 15, and 30 mm for the passage of the vapor-gas mixture, was placed inside the chamber; without the inserts the opening (of the chamber itself) was 50 mm. In experiments with 30 and 50 mm jet openings, the metal discs 6 of 20 and 30 mm diameter were inserted in the jet, to distribute the vapor-gas mixture over the entire section of the jet.

The conditions for the laboratory experiments were the following:

Temperature of the vapor-gas mixture at entry into the jet. . . . . 311°  
 Temperature of the surrounding air . . . . . 20°  
 Volume of air entering the evaporator . . . . . 0.6 m<sup>3</sup>/hour  
 Amount of evaporated glycerin. . . . . 0.328 kg/hour

The results of the experiments are shown in the Table and in Fig. 6. It is seen from these results that the mean diameter of the droplets increases with decrease of the velocity of the vapor-gas mixture in the jet. This is in full agreement with the above views that with decreased velocity of the vapor-gas mixture in the jet, the time during which the droplets remain in the supersaturated vapor zone increases, and the amount of vapor condensed on the droplet surfaces becomes greater, which ultimately leads to an increase of the mean droplet diameter.

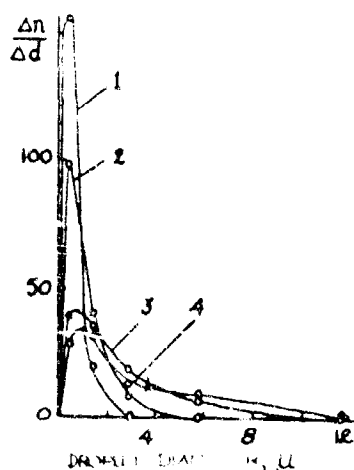


Fig. 6. Differential curves for droplet distribution in the basic experiments, with jet diameters: 1) 2.5; 2) 7.5; 3) 15; 4) 30 mm.

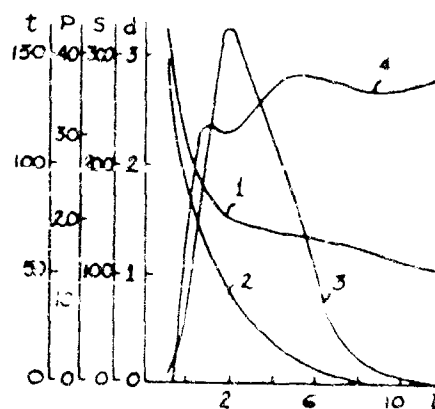


Fig. 7. Values of 1) temperature  $t$ ; 2) vapor pressure  $P$ ; 3) vapor supersaturation  $S$ ; 4) mean droplet diameter  $d$  in the field of the stream at various distances  $l$  from the jet.

The experimental results obtained convincingly confirm the truth of the theoretical views put forward above, and show that the degree of dispersion of liquid aerosols obtained by the condensation method may be varied within fairly wide limits.

The experimental data are in good agreement with the calculated results. The development of calculation methods for the degree of dispersion of liquid aerosols obtained in a stream is of great practical importance. We, therefore, did a great deal of work in order to obtain a sufficiently convenient calculation method.

This calculation is based on the theory of mist formation and the theory of a free stream. The principle of the calculation is that the field of the free stream is broken up into several arbitrary regions, and the values of  $u$ ,  $T$ ,  $P$ ,  $S$ ,  $l$  and  $r$  is determined for each. The mean values of these are taken over the whole region. Together with a calculation of the numbers of the droplets formed and of their dimensions, the amount of vapor condensed on these droplets and the coagulation of these droplets is considered. The results obtained for each region are then used to obtain mean values for the whole field of the free stream.

A full calculation was made for the experiment with a jet diameter of 2.5 mm. The field of the free stream, in which the vapor condensation process begins and ends, was broken up into 31 regions, and all the values were determined for each region.

Fig. 7 shows the calculation results. The abscissa axis shows the distance of the region from the edge of the jet, and the ordinate axis gives the values of  $t$ ,  $P$ ,  $S$ , and mean droplet diameter. It is seen from the Figure that with increasing distance from the edge of the jet the values of  $t$  and  $P$  gradually decrease. The mean diameter of the droplets at the end of the process is 2.6  $\mu$ . From the experimental data this value is 1.6  $\mu$ . The agreement is fairly close.

The higher value of the mean droplet diameter obtained by calculation is explained by the fact that the mean vapor supersaturation in each region is assumed in the calculation. In fact, the vapor supersaturation varies considerably over the cross-section and the rate of formation of droplets in the region varies correspondingly. Therefore, the calculation gave a smaller number of droplets, and consequently the mean diameter obtained was greater.



Degree of Dispersion of Glycerin Aerosol: Relation to the Jet Diameter

Jet diameter, mm	Number of droplets, in %, having the diameter, in $\mu$						Mean droplet diameter, in $\mu$
	0-1	1-2	2-4	4-8	8-16	16-32	
2.5	77.7	19.9	2.3	—	—	—	1.59
7.5	48.4	32.3	11.3	0.9	0.03	—	2.85
15	19.3	34.5	27.3	17.9	0.93	—	5.58
30	—	24.4	26.6	43.0	5.74	—	7.31
50	14.1	30.4	18.9	26.1	10.0	0.41	9.99

SUMMARY

1. The influence of various factors on the degree of dispersion of liquid aerosols obtained by the condensation method in a free stream has been established.
2. The possibility of regulation of the mean droplet diameter by variation of the rate of mixing of the gas streams has been confirmed.
3. Principles are put forward for calculation of the degree of dispersion of liquid aerosols obtained by the condensation method in a free stream, and calculation results are given for the mixing of glycerin vapor with atmospheric air.

The Ya. V. Samoilov Scientific Institute for  
Fertilizers and Insectofungicides, Moscow

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